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Landfill Decomposition Gases

an annotated bibliography

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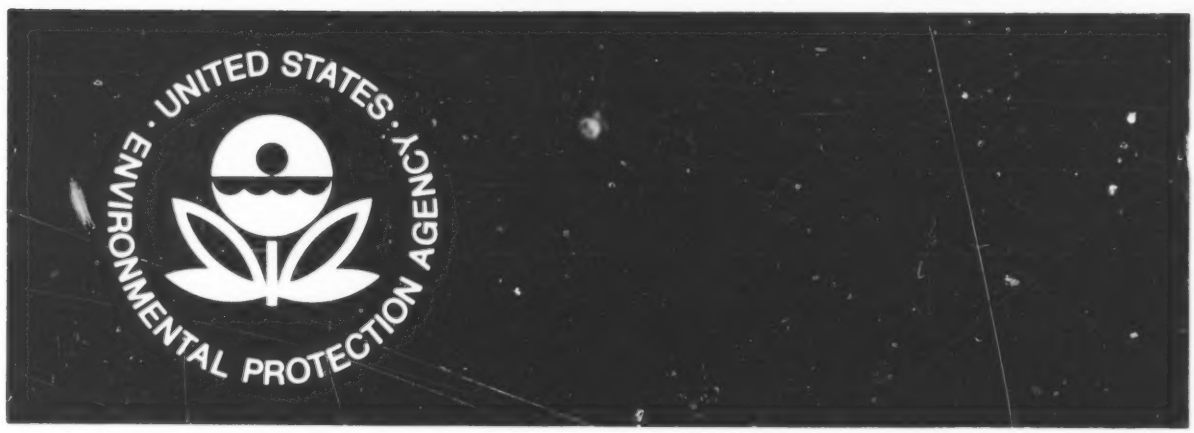
AN ANNOTATED BIBLIOGRAPHY



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This bibliography contains 48 articles on a variety of research studies, case studies and observations on gases generated by the decomposition of landfilled refuse. It includes annotations of articles on landfill gas generation and generation rates, gas composition, gas movement rates and travel distances, and gas control techniques.

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LANDFILL DECOMPOSITION GASES

AN ANNOTATED BIBLIOGRAPHY

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June 1972

ABSTRACT

This bibliography contains 48 articles on a variety of research studies, case studies and observations on gases generated by the decomposition of landfilled refuse. It includes annotations of articles on landfill gas generation and generation rates, gas composition, gas movement rates and travel distances, and gas control techniques.

FOREWORD

To find, through research, the means to protect, preserve, and improve our environment, we need a focus that accents the interplay among the components of our physical environment – the air, water, and land. The missions of the National Environmental Research Centers – in Cincinnati, Research Triangle Park, N.C., and Corvallis Ore. – provide this focus. The research and monitoring activities at these centers reflect multidisciplinary approaches to environmental problems; they provide for the study of the effects of environmental contamination on man and the ecological cycle and the search for systems that prevent contamination and recover valuable resources.

Man and his supporting envelope of air, water, and land must be protected from the multiple adverse effects of pesticides, radiation, noise, and other forms of pollution as well as poor management of solid waste. These separate pollution problems can receive interrelated solutions through the framework of our research programs – programs directed to *one* goal – a clean livable environment.

This publication, published by the National Environmental Research Center, Cincinnati, reports on work from this center. *Landfill Decomposition Gases: An Annotated Bibliography* contains reference information on landfill gas generation, gas movement, and gas control. Municipalities, consultants, researchers, and others concerned with gas production in sanitary landfills should find this publication useful. Sanitary landfilling is, in most instances, one of our most environmentally sound methods for disposing of the continually mounting mass of solid wastes generated by the people of our country.

ANDREW W. BREIDENBACH, Ph. D.
Director, National Environmental
Research Center, Cincinnati

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PREFACE

Sanitary landfilling is one of today's best available methods of solid waste disposal. It is usually neat, safe, and inexpensive; we often forget, however, that the decomposition of solid waste can continue for many years. Decomposition of organic wastes will yield gaseous products such as methane and carbon dioxide that can have serious effects on the environment. Carbon dioxide will dissolve in groundwater and thus contribute to increased hardness and higher concentrations of pollutants. Methane is highly flammable and, when trapped in a closed space, can create serious explosions. There are recorded instances of both water-well contamination by carbon dioxide intrusion and deaths by methane explosions. Additional air pollution problems sometimes arise from noxious decomposition odors. Controlling the environmental impact of refuse decomposition gases is an essential part of proper sanitary landfilling techniques.

This annotated bibliography attempts to document all known publications on landfill gases for use in solving these environmental problems. Most of these articles are nonscientific and several are outdated. The older articles contain statements and concepts that reflected landfill technology current with the time of the article. Some of these statements and concepts are no longer valid because of more recent findings from research studies and field monitoring. The conclusions and findings reported here do not necessarily represent the policy position of EPA.

Several annotations have been taken directly from two other solid waste bibliographies: *Solid Waste Management Practices: An Annotated Bibliography and Permuted Title and Key-Word Index*, Oak Ridge National Laboratory, and *Solid Waste Management: Abstracts and Excerpts from the Literature*, University of California, Berkeley. These annotations are noted by (OR) and (UC) respectively.

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LANDFILL DECOMPOSITION GASES

AN ANNOTATED BIBLIOGRAPHY

AMERICAN PUBLIC WORKS ASSOCIATION, *Municipal Refuse Disposal*, 2d ed., Chicago, Public Administration Service, p. 128-132, 134, 135 (1966).

Decomposition of landfills depends on many factors including permeability of cover material, depth of burial and rainfall, moisture content and putrescibility of the refuse, and degree of compaction. Refuse is composed primarily of carbohydrates, fats, and proteins, which decompose to form humus and the gaseous end products of carbon dioxide, methane, ammonia, and hydrogen sulfide. Anaerobic decomposition occurs at elevated temperatures—usually 100 to 120 F, but sometimes as high as 160 F.

Methane and carbon dioxide are the principal gases produced during refuse degradation. Gas production has been noted to decrease as moisture decreases. Hydrogen sulfide occurs when sea water is allowed to enter a landfill.

Landfills may require many generations to completely decompose. Studies in California estimate possible total decomposition times of over 950 years. California also found that sizable carbon dioxide concentrations will persist for many years and that landfill gases will dissolve in groundwater.

A listing of the landfill gas control rules of the 1959 American Public Works Congress is presented. The rules are used as guidelines for safe building construction on completed sanitary landfills, and they are based on the concepts that subsurface gases can be intercepted and dissipated and that gases can be arrested by using subsurface enclosing envelopes of gastight construction.

ANDERSON, D. R., and J. P. CALLINAN, "Gas Generation and Movement in Landfills," In *Proceedings: National Industrial Solid Wastes Management Conference*, Houston (Mar. 1970).

A theoretical study of gas movement and gas generation was applied to a hypothetical landfill. By comparing a sewage digester

and the hypothetical landfill, it was theorized that a well-established buffer system is important for optimal landfill gas production. The aerobic processes that involve carbon dioxide production generate moisture that helps establish a buffer system for anaerobic methane production. Theoretically, a pound of refuse can produce 2.7 cubic feet of carbon dioxide and 3.9 cubic feet of methane.

Gases flow through porous media by molecular effusion, molecular diffusion, and convection. It was concluded that in landfills the primary gas movement mechanism is convection and the basic rate equation is Darcy's Law. The convection theory was then applied to a two-dimensional landfill analogue (on electrical conducting paper) predicting movement patterns.

BAUMAN, L. "Decomposition Creates Danger in Landfill," In *1964 Sanitation Industry Yearbook*, p. 29.

In this short non-technical article, Bauman discusses methane gas build-up in landfills that caused scares in Arlington, Mass., and the Borough of Queens in New York City. After detecting methane in and around buildings near the landfills, both cities constructed gravel trenches to intercept and dissipate the gas.

BEVAN, R. E., *Notes on the Science and Practice of the Controlled Tipping of Refuse*, London, The Institute of Public Cleansing, p. 26-27 (1967).

The results of a refuse disposal field study in England are reviewed in a brief section of the book. In practically every case the reactions caused by bacterial activities on organic materials result in the formation of a gas of some kind. The gases found in the Wythenshawe study plots were hydrogen, methane, nitrogen, carbon monoxide, oxygen, sulphuretted hydrogen, and carbon dioxide.

Only two of the gases found, sulphuretted hydrogen and carbon monoxide, are definitely poisonous. Only small traces of sulphuretted hydrogen were detected in the plots and at no time in the outside air. The carbon monoxide level seldom reached 1.0 percent inside the test plots and was never at dangerous levels near the surface or outside the plots.

Hydrogen, carbon monoxide, and methane might form explosive mixtures when combined with air in certain proportions. Not at any time, however, have any of these gases been present along with oxygen in the correct proportions for the formation of an explosive mixture; because the ignition temperature for any one of the mixtures is very much higher than any recorded in the plots, no danger is to be apprehended from the explosion hazard.

The tip is nonodorous after sealing, unless specially pierced (as when taking samples); in any case the odors, even within the tip, are of short duration.

BISHOP, W. D., R. C. CARTER, and H. F. LUDWIG, "Gas Movement in Landfilled Rubbish," *Public Works*, 96(11):64-68 (Nov. 1965).

This is a report on one of the more scientific studies of landfill gas movement. The objectives of the research study were to evaluate the types and quantities of gases produced in landfills and the movement of these gases horizontally and vertically. The test cell contained 22,950 cubic yards (4,290 tons) of domestic rubbish, which was placed in three 6- to 7-foot layers in an abandoned gravel pit.

Gas sampling probes were positioned both inside and outside the test cell. Carbon dioxide concentrations ranged from 60 to 70 percent, with one probe reaching a maximum of 89.4 percent. Over 80 percent of the gas probes had reached their respective maximum carbon dioxide concentrations within 11 days after covering the test cell. Hydrogen and methane concentrations reached maximums of 14 and 29.6 percent, respectively.

Carbon dioxide movement velocities through the landfill's surrounding soils were estimated by using an approach basically the same as that involved in determining the flow-through time in a sedimentation tank. These "gross" velocities were calculated by dividing the travel time (the difference between the date of initial appearance of carbon dioxide and the date at which the carbon dioxide concentration reached equilibrium) into the distance from the refuse to the sample probe. The mean "gross" vertical and horizontal velocities were 0.22 foot/day and 0.24 foot/day, respectively.

The "net" quantity of carbon dioxide passing through a certain area was calculated with the use of the following equation:

$$Q = V \times \frac{A_v}{100} \times \frac{C}{100} \times W$$

where Q = net quantity of carbon dioxide (pounds/day)
V = "gross" velocity (feet/day)
A_v = percent of void area
C = percent concentration of carbon dioxide
W = unit weight of carbon dioxide

The calculations established that the amount of carbon dioxide entering the soil was: vertically, 18,700 pounds/year; horizontally, 3,300 pounds/year. This is equivalent to 5.1 pounds/year for each ton of refuse in the test cell.

BISHOP, W. D., R. C. CARTER, and H. F. LUDWIG, "Water Pollution Hazards from Refuse-Produced Carbon Dioxide," *Journal of Water Pollution Control Federation*, 38(3):328-329 (Mar. 1966).

This paper is one of the many reports on the Azusa landfill gas movement studies conducted in southern California. The project studied vertical and horizontal gas movement from a pilot scale landfill placed in an abandoned gravel pit.

A noteworthy portion of this article discusses gas movement theory and compares actual and theoretical results. Movement downward results from molecular diffusion plus density differences, whereas movement to the sides and upward to the atmosphere results from diffusion alone. On a theoretical basis, one can calculate the magnitude of diffusion into the soil and the atmosphere from two different solutions of Fick's Law of Molecular Diffusion. One can also calculate the flow due to density differences in accordance with Darcy's Law, assuming that large pressure differences will not occur and that the gases may be treated as incompressible fluids.

The results of both the theoretical and actual calculations for carbon dioxide movement are as follows:

Direction	Time (days)	Observed Diffusion (lb/acre/yr)	Theoretical Diffusion (lb/acre/yr)	Density Convection (lb/acre/yr)
Vertically downward	550	24,400	19,100	12,800
Horizontally	550	22,700*	25,400*	–
Upward through cover	718	1.9×10^5	9.2×10^5	–
	809	3.0×10^5	9.2×10^5	–

*Acre of vertical interface.

BRUNNER, D. R., and D. J. KELLER, *Sanitary Landfill Design and Operation*, Rockville, Md., U. S. Environmental Protection Agency, p. 56-61 (1971).

A general discussion of landfill gases – their properties and hazards – is presented. Two types of gas control methods can be used: permeable and impermeable. The permeable controls consist of gravel trenches, pipe venting, and pumped exhaust wells. Clay liners and synthetic membranes are impermeable controls. The authors include excellent diagrams, explaining how landfill gas control systems work.

BURCH, L. A., "Solid Waste Disposal and its Effect on Water Quality," *California Vector Views*, 16(11):99-112 (Nov. 1969). The following abstract is taken directly from the publication:

> The disposal of solid wastes can cause impairment of ground or surface water quality. The complex relationships between solid

waste disposal and water quality are summarized in this general discussion. Many types of municipal, industrial, and agricultural solid wastes exist in forms which when disposed of improperly may be sources of water pollutants. A relatively small number of incidents of water quality impairment are on record, perhaps resulting in complacency regarding this hazard. Some of the more significant studies of this subject have been conducted in California and are reviewed in this discussion. Solid wastes can be sources of water pollutants by three processes: (1) physical removal, (2) leaching, and (3) gas production, resulting in water quality impairment in the form of floating debris, increased mineral content, discharge of microorganisms, and potential release of toxic substances.

This paper describes the possible effect of solid waste disposal on ground water and surface water. Ground water may be adversely affected by leaching soluble materials out of a landfill resulting in the discharge of these pollutants into the ground water. Carbon dioxide gas may also cause increased hardness and corrosiveness of the ground water. Surface water can be impaired by dumping solid wastes directly into the water or by the physical erosion of portions of landfills located in floor plains during flood conditions. Measures available for control and prevention of water quality problems from solid waste disposal are also briefly discussed. These include categorization of solid wastes for their disposal in landfills qualified to accept them due to the physical characteristics of the disposal site. Also discussed are landfill construction and operation techniques and application of water during the final use of the landfill. Research which is now under way is envisioned to provide some of the answers needed to preclude water quality impairment from solid waste disposal.

BURCHINAL, J. C., and H. A. WILSON, *Sanitary Landfill Investigation*, Final Report, Research Grant No. SW-00040-01, 02, 03, Department of Health, Education, and Welfare, unpublished (Aug. 1966).

The authors undertook, over a 2½-year period, a laboratory research study of the production of gas and volatile acids from sanitary landfills with the use of steel cylinders filled with refuse. The use of ground and unground refuse was compared by studying the pattern of gas generation. Emphasis was placed on biochemical actions occurring in sanitary landfills. Temperature, volatile solids, and C/N ratios proved to be unsatisfactory parameters for defining the course of decomposition. Analyses of gas and volatile acids

produced as a result of microbial metabolism provided evidence as to mechanisms involved in the process.

Some of the more significant results and conclusions included in the paper are:

1. Hydrogen, oxygen, nitrogen, carbon dioxide, and methane would be the major gases in a normally constructed sanitary landfill. Trace amounts of hydrogen sulfide could be formed in the first week, but the chance of its presence beyond the part per million level in the first 2 years would be small. The landfill would not release gaseous ammonia except under high pH conditions.
2. Hydrogen was produced in great quantities during the first 3 weeks. The maximum content of 20.6 percent was produced between the first and second week. It declined to about 1 percent at the end of 1 month but was present at the 0.1 percent level over the years investigated. The presence of molecular hydrogen was indicative of the reducing system operated at an oxidation-reduction potential well below that of the hydrogen electrode and was also evidence of anaerobic conditions.
3. Two weeks after placement of refuse, carbon dioxide was produced to a maximum of 85 percent. Following the maximum peak, the content of carbon dioxide rapidly reduced and approached 40 percent at the end of 2 months. The rate of change in carbon dioxide after the sixth month was small and generally stayed in the level of 40 percent.
4. Trace amounts of methane were produced during the second week. In one of the cylinders, it reached 2.7 percent at the end of 2 months, 6 percent in the sixth month, 13 percent at the end of 1 year, and 20 percent at the end of 2 years. Other cylinders showed much lower methane contents. Low pH and trace amounts of oxygen could inhibit methane bacteria. Saturation of refuse with water would probably enhance methane production.
5. Stratification of gases occurred within the cylinders. Contents of carbon dioxide, methane, and hydrogen were higher in the lower portion, whereas the content of nitrogen was higher in the upper portion.
6. Composition of gas in landfills was related to compaction densities of refuse, particularly in the early period when production of carbon dioxide and hydrogen was high. With the higher compaction density, there is less void space within the refuse, but more organic materials available per unit volume to produce gases.

7. Results of both gas and volatile acids analyses indicated that the most pronounced changes in organic materials occurred within the first 60 days. Accumulation of intermediate products indicated, however, that organic materials in landfills were far from stabilized even at the end of 2 years.

CALIFORNIA DEPARTMENT OF WATER RESOURCES, *Sanitary Landfill Studies, Appendix A: Summary of Selected Previous Investigations,* Bulletin No. 147-5, Sacramento (1969).

The authors of this publication summarized the major landfill research studies conducted in southern California. The following abstract appeared in the publication:

Three principal techniques used for the disposal of refuse are incineration, open dumps, and sanitary landfills, of which landfills are the most useful and effective. This report not only gives information on landfills from investigations by the Department of Water Resources, but also summarizes the work of other investigators. / Decomposition of refuse in landfills results in the formation of gases. If sufficient water is available, these gas products may dissolve. Soluble organic and inorganic compounds may also be dissolved, forming leachate. / Instances of gas and leachate impairment of ground water are cited in this report. All of which indicate the necessity for control measures. They show that sanitary landfills should be designed as a system, with prime consideration given to site selection, materials to be deposited, construction and operation techniques, and use of the completed fill. / The report describes a system for classifying the physical characteristics of a site according to the degree of protection afforded receiving waters and for determining what type refuse could be disposed in each.

CALIFORNIA STATE WATER POLLUTION CONTROL BOARD, *Effects of Refuse Dumps on Ground Water Quality,* Publication No. 24, Sacramento, p. 47-67 (1961).

Decomposition processes and rates are believed to be closely connected with the circulation of air and decomposition gases through refuse fill. Gas movement can occur by displacement when there is a net production or uptake in the refuse and by convection due to differences in gas density. Density variations may arise when portions of the refuse atmosphere receive heat liberated in the decomposition process and when the gas produced has an average molecular weight different from that of air. However, the most effective transfer mechanism is molecular diffusion; the diffusivity of a porous medium is relatively independent of the particle size, so gases may diffuse readily through some materials of low permea-

bility. Therefore, in preventing carbon dioxide from moving into the underground, methods that involve its removal to the atmosphere by encouraging draft or ventilation may be more effective than coatings to decrease permeability of the disposal pit surfaces.(UC)

The report includes discussion of the basic aerobic and anaerobic processes that generate landfill gases and the quantities of gas that might be produced. A description of landfill gas properties and a good explanation of gas movement by diffusion and convection are also presented. The theories for generation and movement are substantiated by known data wherever possible.

CALIFORNIA STATE WATER POLLUTION CONTROL BOARD, *Report on the Investigation of Leaching of a Sanitary Landfill*, Publication No. 10, Sacramento, p. 13, 53-56 (1954).

Limited gas study was conducted in conjunction with leaching research at a Riverside landfill site. This section of the report includes information on sampling equipment and techniques and tabulations of gas concentration data from new and old landfill areas.

It was concluded that anaerobic conditions with production of combustible gas will exist within a sanitary landfill in approximately 1 month following deposition of the fill.

Air in the fill is consumed by aerobic decomposition of the refuse. The following are typical oxidation reactions for carbohydrates and stearic acid:

$$C_6 H_{12} O_6 + 6 O_2 = 6 CO_2 + 6 H_2O$$

$$C_{18} H_{36} O_2 + 26 O_2 = 18 CO_2 + 18 H_2O$$

After the oxygen is used up, the anaerobic decomposition of the waste results in an increased quantity of gas (methane and carbon dioxide) which creates increased pressure and subsequent gas diffusion:

$$C_6 H_{12} O_6 = 3 CO_2 + 3 CH_4$$

$$C_{18} H_{36} O_2 + 8 H_2O = 5 CO_2 + 13 CH_4$$

CALIFORNIA STATE WATER QUALITY CONTROL BOARD, *In-situ Investigation of Movements of Gases Produced from Decomposing Refuse*, Publication No. 31, Sacramento (1965).

The authors have compiled in this technical report complete information about all phases of a research project at Azusa, Calif., on the movement of refuse decomposition gases through a landfill.

Because of concern about possible groundwater pollution from use of abandoned gravel pits for disposal of solid wastes, this study was undertaken to evaluate the movement of refuse decomposition gases, both laterally and vertically, through a refuse fill and adjacent strata. Carbon dioxide was the only decomposition gas found in significant quantities in the adjacent and surrounding soil. About 18 times the quantity of carbon dioxide and about 24 times the quantity of methane passed through the 1-foot silt cover into the atmosphere as passed into the surrounding soil. If it is deemed necessary to isolate carbon dioxide from groundwater, control methods must be formulated.

The active "life" of the refuse fill was estimated on the basis of the total carbon initially present in the refuse and on the past and present rates at which carbon has passed out of the fill. On the assumption that the calculated initial amount of carbon was "available," the following projections were made:

Percent of Initial Carbon Gone	Years	CO_2 Concentration in Bottom Refuse Layer
50	57	12 percent
90	950	3 percent

CALIFORNIA STATE WATER QUALITY CONTROL BOARD, *In-situ Investigation of Movements of Gases Produced from Decomposing Refuse*, Final Report, Publication No. 35, Sacramento (1967).

Over 90 percent of the gas produced by refuse decomposition in large landfills is carbon dioxide and methane. Both of these gases were found in concentrations up to 40 percent at distances up to 400 feet away from the edge of the fill. An equal concentration of carbon dioxide can be found in the soil under a landfill if the soil is homogeneous and not impervious. Methane poses less of a threat to groundwater quality because it is only slightly soluble in water. Moreover, since it is lighter than air, it will tend to rise through the landfill rather than diffuse into groundwater.

Refuse gases pose more of a hazard to groundwater than leachates because gases are always produced, whereas the leachate problem is one of external water passing through the refuse. Proper location and maintenance of the fills help avoid leachate problems. A workable and effective carbon dioxide gas barrier membrane was developed. (Using such a membrane would increase the cost of landfill operation by 10 percent or less.) Methane production in pits constructed to test the effectiveness of an asphalt barrier was not great enough to permit a conclusive determination of the

effectiveness of this type of barrier. A more effective gas control procedure would be one in which the gas is vented and burned. (UC)

This publication is one of the best and most comprehensive reports on landfill gases.

CALLAHAN, G. P., and R. H. GURSKE (Bureau of Sanitation, City of Los Angeles) "The Design and Installation of a Gas Migration Control System for a Sanitary Landfill," presented at The First Annual Symposium of the Los Angeles Forum on Solid Waste Management, May 1971, in Pasadena, Calif.

Research on landfill gas control systems at two Los Angeles, Calif., sanitary landfills is summarized in this technical report. The two sites (Branford and Sheldon-Arleta) are constructed in old gravel pits, and in both locations, gas generated from refuse decomposition has migrated beyond the fill area. Extensive tests at both landfills have resulted in the development of an effective method to control gas migration.

After extensive gas movement was discovered, the Branford site was equipped with a gas well test installation. Five wells, spaced on 40-foot centers and gravel filled, were placed at various depths and the withdrawal lines installed in each well were connected to a header and ventilation blower. Several tests determined the efficiency of the various wells at different air flow rates, blower cycle times, and well combinations. It was found that gas migration may be controlled with a well spacing of between 300 and 400 feet with a withdrawal rate as low as 200 cfm per well.

At the Sheldon-Arleta landfill site, three 24-inch diameter wells were drilled and a single withdrawal line installed in each well. The wells were at various depths, gravel filled, and connected to a main header leading to a withdrawal blower. Again, tests utilized different flow rates, blower cycles, and well combinations. The conclusions from the Branford study were confirmed with respect to well spacing and withdrawal rate required. It was also concluded that the withdrawal rate is apparently a function of well spacing and that well depth in the range tested is not a significant factor.

Based on the information obtained from the Branford and Sheldon-Arleta tests, the city of Los Angeles has installed a $115,800 gas control system to protect houses and a high school at the Sheldon-Arleta site. The system consists of 17 wells, 25 feet deep, spaced on 150-foot centers, with a designed withdrawal rate of 200 cfm each. The 2-foot diameter ventilation wells were drilled in natural soil and held a 6-inch diameter perforated PVC pipe packed in gravel. The wells are connected to a vitrified clay pipe header that runs three-fourths of a mile to a 15-horsepower fiberglass blower. The blower feeds an induced draft vapor fume incinerator

that uses natural gas as a supplementary fuel. The system will completely protect the surrounding neighborhood and provide excellent facilities for future gas migration research.

CARPENTER, L. V., and L. R. SETTER, "Some Notes on Sanitary Landfills," *American Journal of Public Health,* 30(4):385-393 (Apr. 1940).

The article is a report on one of the first "scientific" investigations on sanitary landfills. The researchers used gas probes at several different depths to obtain gas concentration data from landfills in "dry" conditions and "wet" (located in water table) conditions. The equipment and procedures used were very crude, but this is the earliest known attempt to collect and identify gases from landfilled refuse.

COE, J. J., "Effect of Solid Waste Disposal on Ground Water Quality," *Journal of the American Water Works Association,* 62:776-783 (Dec. 1970).

Leachate and carbon dioxide from refuse decomposition have been responsible for groundwater degradation in California. Carbon dioxide can impair groundwater by affecting acidity, alkalinity, and hardness.

The California State Department of Water Resources has studied carbon dioxide impairment of groundwater at Azusa and Monrovia (Mayflower Well), Calif. Some of the more important findings from this article that includes detailed summaries of these two studies are:

1. Gas production quantities vary directly with temperature, moisture content, garbage content, and aeration. Dry refuse and saturated refuse produce 0.035 and 0.210 cubic foot of gas per pound of refuse on a dry basis, respectively, as determined experimentally. Gas movement rates were found in this study to be 0.22 to 0.8 foot/day vertically, and 0.24 to 1.4 feet/day horizontally in undisturbed alluvial soils.
2. Carbon dioxide effects on groundwater are increases in hardness and bicarbonate. Depending on the pH after carbon dioxide absorption, water may become corrosive.
3. Pollution does not necessarily occur at the same time a landfill is constructed. Completed fills can exist for years before any effects on groundwater are detected.

The author also describes California's landfill rating system. Landfill sites can be modified—usually by construction of a physical

barrier—to protect the groundwater. The physical barriers used are clay layers, plastic membranes, and asphalt liners. Studies on asphalt and polyethylene sheet indicate carbon dioxide concentrations are reduced 75 percent and 50 to 60 percent, respectively. Future studies will include development of a natural ventilation system.

DUNN, W. L., "Landfill Gas Burned for Odor Control," *Civil Engineering*, 27(11):60-61 (Nov. 1957).

The author discusses an incident at a landfill at the University of Washington grounds in which methane gas was ignited. An inexpensive burner was made by welding a short piece of ¼-inch wire mesh screen onto one end of 1-inch diameter tubing. The screen was then placed 6 to 12 inches into the refuse with earth compacted around it. A low pressure flame retention gas burner was inserted about 2 inches from the top of the tubing. To burn the refuse gas, a tight earth seal had to be maintained.

DUNN, W. L., "Settlement and Temperature of a Covered Refuse Dump," *The Trend in Engineering*, 9(1):19-21 (Jan. 1957).

In this short report on observations made at the Union Bay refuse disposal site in Seattle, Dunn presents several comments on gas and odor problems. A very hot gas fire was discovered in a 20- to 30-foot long settlement crack. There was no smoke, and the surrounding soil was red hot. Gas bubbles were also seen where water had accumulated on the fill surface. Later, a 1¼-inch pipe was driven into the landfill and used as a waste gas burner. Gas burners were then used for odor control at other locations.

DUNN, W. L., "Storm Drainage and Gas Burning at Refuse Disposal Sites," *Civil Engineering*, 30(8):68-69 (Aug. 1960).

On a refuse disposal site loaned by University of Washington to city of Seattle, French drains about 20 feet wide, 10 feet deep, and several hundred feet long were constructed to abduct storm waters and collect gases. Controlled burning at specially constructed inlets oxidized methane and destroyed foul odors. (OR)

This article is a non-technical report of the author's observations at the landfill site.

ELIASSEN, R., "Why You Should Avoid Housing Construction on Refuse Landfills," *Engineering News-Record*, 138(18):90-94 (May 1, 1947).

An early attempt to control landfill gases and odors is recorded.

Erection of veterans' emergency housing units in New York City called for the use of a 130-acre site that had been filled with rubbish and garbage some 5 years earlier. Regrading the site and opening trenches for utilities exposed decomposing garbage with its resulting stench.

A commercial oxidizing agent sprayed on the exposed refuse successfully controlled these odors. To cope with the problem of combustible gas generation within the fill, all the houses were elevated above the ground and an aluminum foil membrane was secured under the wood flooring. On the basis of these experiences, the conclusion is reached that landfills should not be used for purposes requiring excavation. (OR)

ELIASSEN, R., F. N. O'HARA, and E. C. MONAHAN, "Sanitary Landfill Gas Control," *The American City,* 72(12):115-117 (Dec. 1957).

The town of Arlington, Mass., discovered explosive concentrations of methane gas near an old landfill site that endangered several homes and a business. The discovery was originally believed to be a natural gas line leak, but the presence of high carbon dioxide concentrations and no signs of ethane indicated the landfill as the gas source.

A weekly sampling routine was initiated to monitor concentrations and a long gravel trench was installed to intercept and vent the gas. Before the trench was installed, explosive concentrations of gas were consistently recorded 600 feet away from the landfill.

"Explosion and Fire Traced to Refuse Generated Gases," *Refuse Removal Journal,* 6(8):34 (Aug. 1963).

Methane, hydrogen, and ammonia are dangerous gases formed by the bacterial decomposition of organic material. A recent report on a study of the causes behind six cases of fire and explosion from the U. S. Bureau of Mines Explosives Research Laboratory makes this point clear.

An explosion that demolished a nearby house was traced to gases generated by sewage dumped into an abandoned mine.

Gases bubbling through pools of water on a school construction site were found to be flammable, and there was a vegetable decay odor in the area. The investigators from the Bureau's explosives research laboratory found that the building's foundations were located directly over an old garbage dump.

In another investigation, it was discovered that an inflammable gas had been admitted to a house through the accidental connection of a storm sewer to a sanitary disposal pipe line. (OR)

FIRST, M. W., F. J. VILES, Jr., and S. LEVIN, "Control of Toxic and Explosive Hazards in Buildings Erected on Landfills," *Public Health Reports*, 81(5):419-428 (May 1966).

The actual field application of landfill gas control technology on a construction project is discussed in this article. The principal hazard involved in construction on refuse-filled land arises from the anaerobic production of combustible gases. Gastight construction over landfills is difficult if not impossible to achieve because of the gas pressure resulting from biological gas production.

During investigations of gas levels in a housing development constructed on sanitary landfills, the concentration of methane was at an unsafe level in a high proportion of the buildings. A concrete slab laid on top of the fill did not prevent gases from getting into the buildings. Several sealants (Flintkote C-13-A asphalt emulsion; Flintkote No. 70 asphalt emulsion; sodium silicate; water) proved to be inadequate for the purpose.

Results of periodic sampling over several years in the subbasement spaces of a number of buildings indicated that organic fill located around and under the heated buildings became completely degraded in approximately 5 years, releasing methane at a proportionately rapid rate. A situation such as this can constitute a serious explosion hazard unless suitable methods of aeration and ventilation are employed. Continuous mechanical aeration at a rate of one or two air changes per hour adequately reduced the methane concentration. (UC)

FLOWER, F. B., and L. A. MILLER, "Report of Investigation of Vegetation Kills Adjacent to Landfill," New Brunswick, N. J., Cooperative Extension Service, College of Agriculture and Environmental Science, Rutgers University (1969).

Flower and Miller investigated the death of several trees, bushes, and shrubs on land adjacent to a landfill. Most of this vegetation grew within 15 feet of the landfill. The soil was sandy and at the time of the investigation had 2 to 3 inches of frost. It was believed that the frost may have encouraged the gas movement.

The following are the authors' summary and conclusions:

> Excessive amounts of carbon dioxide and combustible gases were found in the soil of the property. The concentrations decreased as distance from the landfill increased.

It appears from the "gross and quick" tests conducted by Flower and Miller that the vegetation deaths at the rear of the property adjacent to the Cherry Hill sanitary landfill could be due to the displacement of oxygen from the root system of the vegetation by gases of decomposition traveling laterally from the landfill. Corrective measures should be taken which will prevent the gases from traveling beneath the property in excessive quantities. This might be accomplished by placing a gas flow barrier in the ground at the rear of the property or by relieving the landfill gas pressure through well pipes.

FUNGAROLI, A. A., *Pollution of Subsurface Water by Sanitary Landfills*, Final Report, Research Grant No. R01-UI00516, Department of Health, Education, and Welfare, p. 28, 47-51, unpublished (1970).

In this landfill study of a laboratory-scale fill in a lysimeter and a field-scale fill, gas-concentration histories were kept for over 2 years. The report describes the sampling probes and procedures and discusses the gas analysis employed.

"A Gas Control and Monitoring System," *Public Works*, 101(12):39 (Dec. 1970).

The following is the entire article as it appeared in the periodical:

> Engineering Sciences is serving as a special consultant to the firm of McKee, Berger, Mansueto, Inc (MBM), project managers for construction work under way for the University of Massachusetts at Boston. C. Ronald Rabin is the MBM Project Manager. The construction is taking place on a completed dump site and significant quantities of methane gas and traces of hydrogen sulfide have been identified and located, and ES is developing a gas control and monitoring system and the design of facilities to protect against the movement and dangerous concentration of gases.
>
> Following identification of the gases, probes and monitoring with gas detection equipment were used to develop gas concentration contours, and a gas control system (consisting of three principal devices) is being designed to permit safe building occupancies. The primary device is a gas evacuation network composed of perforated piping, collectors, and variable speed pumps which will remove gases from under the buildings. A barrier mat will be installed before the floor slab is poured and all utility entries will be sealed to prevent any gases from entering

the buildings. A safeguard monitoring system will also be installed to detect the presence and concentration of methane and to activate the gas evacuation pumps. The monitoring system will also provide a total check on the system performance.

"Gas Fire in Sewer Manhole Traced to Sanitary Fill Operation," *Engineering News-Record*, 139(26):51 (Dec. 25, 1947).

Because of bad weather, the city of Knoxville, Tenn., sealed off its 3-year-old landfill with clay earth. Within 2 weeks, blue flames and intense heat poured out of a sewer manhole located in the fill. Methane gas from the decomposition in the landfill had seeped through the sides of the manhole and ignited; this caused the manhole to act like a giant Bunsen burner.

The article is a short description of the incide[illegible].

"Gas Fires in a Sanitary Fill," *Engineering News-Record*, 140(2):86-87 (Jan. 8, 1948).

San Francisco's landfill experienced several gas fires caused by spontaneous combustion of venting gases. The fill, located in a tidal area, was 50 to 60 feet deep and was believed to have decomposition temperatures of 160 to 180 F. The gas fire flames were notably low temperature and colorless.

A crude sampling port was dug 5 feet deep into a 12-year-old portion of the fill. Because the sample port was not airtight, the observers did not know if air was present inside the fill. Assuming that all the air in the sample leaked in from the atmosphere, the gas analysis was 25 percent carbon dioxide, 60 percent methane, 9 percent hydrogen, and 6 percent nitrogen.

It was believed that an anaerobic condition existed because of the limited amount of degradation on 12- to 15-year-old refuse samples taken from the fill.

"How to Use Your Completed Landfills," *The American City*, 80(8):91-94 (Aug. 1965).

A survey of counties that used sanitary landfill for their solid waste disposal showed that 48 percent of the 208 that responded to the survey did not have any structures on the completed landfill sites, 21 percent had built on one or more sites, and 31 percent had not as yet completed any landfills. Settlement, gas production, or both have adversely affected many of the structures constructed on completed sanitary landfills.

The article describes responses from many counties throughout the Nation. In general, the consensus was that buildings must have adequate protection from settling and gas seepage. One city initiated the following requirements: a monolithic, self-supporting foundation slab, keyed and sealed foundation walls, a plastic seal under the interior floor, and a 24-inch-wide rock-filled trench around the foundation to collect gas.

Golf courses, playgrounds, parks, and picnic areas are suitable uses for completed landfills, although gases produced by the decomposing refuse often make it difficult for grass and other flora to grow.

"Is There Danger Where There Is Decomposition?" *The Surveyor*, 104:817 (Dec. 28,1945).

The author regards carbon dioxide as a poisonous gas and cites three suffocation accidents in which eight men died. Because it is heavier than air, carbon dioxide will collect in low areas such as sumps and manholes; since it is generated by waste decomposition, it is a hazard around refuse fills, sewage digesters, and septic tanks.

LIN, Y. H. *Acid and Gas Production from Sanitary Landfills*, dissertation, West Virginia University, p. 36-44, unpublished (1966).

A laboratory research study was conducted on three simulated landfills placed in 8-foot by 2-foot-diameter steel cylinders. Gas concentration histories were recorded for hydrogen, oxygen, nitrogen, methane, carbon dioxide, ammonia, and hydrogen sulfide produced in the cylinders.

The report includes gas concentration plots for the first 2 months of the study and a discussion of the microorganisms involved with refuse decomposition. (This dissertation was done in conjunction with a larger research study at West Virginia University. For additional information, see the annotation on Burchinal, J.C., and H.A. Wilson.)

MAC FARLANE, I. C., "Gas Explosion Hazards in Sanitary Landfills," *Public Works*, 101(5):76-78, 138 (May 1970).

After conducting a literature search on gas production in refuse disposal sites, the author presents a broad discussion of landfill gases, some case histories of construction problems on landfills, and a very good list of gas control recommendations.

Most studies indicate carbon dioxide is the principal gas produced in landfill degradation, and maximum concentrations are usually reached early in landfill life. Methane gas can also attain

high concentrations, but this usually occurs after the carbon dioxide peak is reached. Hydrogen sulfide has been a problem in areas where sea water has been allowed to enter the fill. Small quantities of hydrogen and carbon monoxide have also been noted.

Because gas production will continue for many years, the author suggests several excellent points to ensure safety in dwellings constructed on landfills. He recommends that:

1. Vents be installed in the fill to bleed away the gases when slight pressures develop. These can simply be perforated pipes driven into the fill and open to the atmosphere.
2. In addition, a granular material such as crushed stone, gravel, slag, or sand be placed over the fill to encourage uniform diffusion of gas into the atmosphere.
3. Structures designed for sanitary landfills be constructed with gas-tight membranes beneath the ground floor slab. Ordinarily, a well-constructed polyethylene membrane, preferably in two layers and laid on a clear sand fill, will be sufficient. Care must be taken that the fill is not coarse enough to puncture the membrane during construction.
4. Care be taken to provide vapor barriers around all breaks in the foundation.
5. The design eliminate any pockets, depressions, or unwanted dead areas beneath or around the structure where gas might accumulate.
6. When structures are built adjacent to a sanitary landfill, garbage dump, etc., special precautions be taken to prevent the channelling of combustible gases from these areas.
7. If there is a possible hazard in a closed area, it be ventilated to keep the combustible contents in the atmosphere below the lower limit of flammability (natural ventilation is adequate for methane concentrations of less than 1 percent; forced ventilation is advisable where methane concentration is greater than 1 percent).

"Measuring Gas Escape from a Landfill," *Public Works*, 95(9): 163 (Sept. 1964).

To measure the carbon dioxide escape from landfill cover, a device was developed incorporating copper wool saturated with potassium hydroxide to absorb any carbon dioxide escaping from the fill cover. Additional weight of the absorber represented carbon dioxide collected over a given time period. However, the amounts collected in test runs did not agree with theoretical diffusion equations for carbon dioxide escaping to the atmosphere. Refine-

ments were being made to the device and measurements were to continue. The device was expected to be useful in determining the necessary thickness of landfills. (OR)

This brief article completely describes this unique sampling device and how it works.

MERZ, R. C., *Investigation to Determine the Quantity and Quality of Gases Produced During Refuse Decomposition,* Final Report, Los Angeles, University of Southern California, Department of Civil Engineering (Aug. 1964).

In laboratory experiments in which eight 55-gallon drums were filled with garbage, paper, and grass, researchers at the University of Southern California measured the quantity and determined the composition of the gases produced by the decomposition of the material in the drums over a 9- to 11-month period.

Results of the experiments showed that the volume of gas production is definitely related to the moisture content of refuse. Gas production generally was higher in drums that received the larger amounts of water. The volume of gas production also varied with the amount of grass and garbage in the refuse. Aerated drums produced more gas than did those not aerated.

The greatest percentage of the gases was in the form of carbon dioxide and nitrogen. The amount of carbon dioxide production increased in volume as the tests continued. Methane was not found in measurable volumes in the drums. (UC)

MERZ, R. C., and R. STONE, *Factors Controlling Utilization of Sanitary Landfill Site.* Final Report, Research Grant UI 00518, Department of Health, Education, and Welfare, unpublished (July 1963).

Five 20-foot-deep refuse cells were placed partially above grade in a virgin area at a southern California landfill site. A sixth cell was placed entirely above grade and allowed to remain aerobic. Refuse was placed in the cells under varying conditions of moisture content and compaction. All cells were monitored for gas generation at depths of 6 and 15 feet.

The gases produced within the anaerobic cells consisted chiefly of carbon dioxide and nitrogen with varied concentrations of methane depending on refuse moisture content. Surface irrigation markedly increased methane production. The gases were found to diffuse from the cells laterally and downward into the soil and upwards through the cover material. Landfill gas pressures as high as 13 inches of water were recorded. The report includes many tables and graphs explaining the gas concentration histories of the test cells.

MERZ, R. C., and R. STONE, "Gas Production in a Sanitary Landfill," *Public Works*, 95(2):84-87, 174, 175 (Feb. 1964).

The authors report on their 3-year study of landfill gas problems. Among the statements and conclusions from this field-scale landfill project are:

1. Gases produced within the anaerobic test landfills consisted chiefly of carbon dioxide and nitrogen. The concentration of methane depended on moisture content and varied from little more than a trace in the landfill to which no water was added to the major component (greater than 50 percent) of the gas produced in a saturated landfill. Only very small amounts of hydrogen were present.
2. Gases produced in the aerobic fill consisted chiefly of carbon dioxide and nitrogen. Oxygen did not exceed 10 percent.
3. Methane production increased markedly with surface irrigation of the fill.
4. Gases within the four landfills appeared to be under positive pressure and diffused laterally and vertically downward into the surrounding earth as well as upward through the top cover.
5. Small concentrations of oxygen were frequently found in all fills.
6. Initial peak temperature was reached in 3 months and occurred at various depths. Temperature peaks reached during the latter stages of the decomposition were never as high as the original peak.
7. Initial temperatures in the aerobic fill greatly exceeded those in the anaerobic fills. (UC)

MERZ, R. C., and R. STONE, "Quantitative Study of Gas Produced by Decomposing Refuse," *Public Works*, 99(11):86-87 (Nov. 1968).

In this article, the authors describe the results of a field study in which approximately 15 tons of refuse were encapsulated in a 10,000-gallon underground storage tank. In the filling process, a 6-inch layer of sand was placed in the bottom of the tank; then refuse was added and a gas-sampling pipe installed. The refuse consisted of paper (42 percent), grass and garden clippings (38 percent), plastic (3 percent), glass (5 percent), metal (7 percent), and dirt (5 percent). Water was added to bring the moisture content to 69.9 percent (dry weight basis). The in-place density of the refuse was 634 pounds/cubic yard. After filling, the top of the tank was sealed.

About 39.3 cubic feet of gas were produced during the first 3 days after sealing. However, gas production was negligible by the

end of 60 days and continued so until about the 230th day. Thereafter, production was resumed, and a total of 2,025 cubic feet of gas were produced during the period 230 to 530 days after initiation. Production again dropped after the 550th day and from the 550 to 750 day was about 27.5 cubic feet gas/cubic yard refuse.

The temperature ranged from 78 to 100 F during the first 300 days, and from 105 to 120 F during the period of 350 to 475 days. The deep level (14 feet) temperature probes failed during the later stages of the study; hence, no firm figures are available for that period. (UC)

MERZ, R. C., and R. STONE, "Sanitary Landfill Behavior in an Aerobic Environment," *Public Works*, 97(1):67-70 (Jan. 1966).

An aerobic landfill test cell was constructed and was provided with an access well in which outlets for gas collection lines, leach collection lines, and electrical leads could be located. The researchers also gained access through the well to place equipment and obtain data.

A piping system to admit air also was installed. To prevent the air from being forced through the earth cover into the atmosphere, an impervious polyethylene membrane was stretched 1 foot below the surface. The total rate of settlement over 344 days was 1.66 feet, a shrinkage four to six times greater than that occurring under anaerobic conditions.

The chief components of the gas taken at the top and bottom levels were nitrogen, methane, oxygen, and carbon dioxide. At times hydrogen was detected. The temperature was higher and had a greater range in the aerobic cells than in the anaerobic cells. In the former, it ranged from 113 to 193 F at the 10-foot level. Gases discharged from both aerobic and anaerobic cells had an objectionable odor. (UC)

MERZ, R. C., and R. STONE, *Special Studies of a Sanitary Landfill*, Final Summary Report, Distributed by National Technical Information Service, Springfield, Va., 22151, as PB 196 148 (1970).

Scientific field investigations were conducted to determine among other things the quality of gas produced in landfills and the volume of gas produced by a known refuse quantity. The experiments were conducted in four test cells: A and B were under normal anaerobic conditions, C was equipped with a mechanical aeration system, and D was placed in a large steel tank and sealed. Varying amounts of water were added to cells A and B.

After 2 years, cells A and B were generating gas with equal concentrations (nearly 50 percent) of carbon dioxide and methane. Cell C during aeration was found to emit little carbon dioxide or methane but high concentrations of oxygen and nitrogen. Cell D contained 73 cubic yards of refuse and produced 2,027 cubic feet of gas over 907 days. Coring revealed extensive decomposition in the aerobic cell (C), but little decomposition in the two anaerobic cells (A and B).

"Methane Gas Explosions Delay Building on a Landfill," *Solid Wastes Management - Refuse Removal Journal*, 12(7):20 (July 1969).

The article describes an accident in Atlanta, Ga., which was caused by the explosion of an accumulation of methane gas generated by anaerobic decomposition of refuse. Two workmen were killed and four others escaped with minor injuries. The men were working in a building located in a recreation center. In 1961 the area around the building was used as landfill, and as a consequence, the level of the ground was raised several feet. The original structure was 90 feet long by 40 feet wide, one story high, and had a 17-foot-high basement. As a part of the renovation of the building, all windows in the basement were bricked up and the land around the building was filled to the level of the first floor. Except for one stairway all entries between the first floor and the basement were closed. The opening was fitted with a tight-fitting trap door. Later, the entire floor was covered with tile.

The explosion occurred later when gas piping was installed. All gas connections and appliances had been found to be gastight. A workman noted a draft coming through the casing around a gas pipe. The explosion occurred when a plumber was in the process of lighting a cigarette. Later investigation ruled out the possibility of leakage from the gas pipes and furnished convincing evidence that methane coming from the surrounding landfill had accumulated in the building.

The article also mentions another explosion resulting from methane escaping from a reclaimed dump. This explosion ripped apart a swimming pool under construction in Montreal, Canada. Geologists claim that solid wastes in a landfill ordinarily take from 10 to 25 years to decompose. (UC)

ROGUS, C. A., "Use of Completed Sanitary Landfill Sites," *Public Works*, 91(1):139-140 (Jan. 1960).

Since 1898, New York City has landfilled about 300,000,000 cubic yards of material; about 10,000 acres of tidal and marshy

lands have been reclaimed. As the refuse decomposes, hazardous methane gas may be generated and escape from the landfills through cracks in the cover material. Since the decomposition process is very slow, the methane gas hazard may persist for many years. For this reason, the city requires that all buildings erected on completed landfills be protected from methane gas by using gastight construction and adequate ventilation.

The author sets forth a good list of minimum gas-control construction requirements for residences, multiple dwellings, and industrial and commercial buildings.

"Sanitary Landfill Tests Investigating Refuse Volume Reduction and Other Phenomena," SED Research Report No. 21, *Journal of the Sanitary Engineering Division,* ASCE, 83(SA6):Paper 1853:1-3 (Nov. 1958).

At the Union Bay sanitary landfill disposal site, Seattle, Wash., tests have been performed over a 1-year period to ascertain compaction, settlement, fill temperature, and gas production. These data are critically reviewed with reference to obtaining optimum refuse disposal volume into a given landfill area.

Relatively large quantities of combustible methane gas and some carbon dioxide gas were reported to be generated in the fill. Analyses indicated that a fraction of less than 1 percent other gases were also continuously evolved throughout the test year. Most gas production occurred 6 to 24 months after the landfill was in place. Landfill areas receiving additional moisture and containing greater refuse fill depths were reported to have increased gas production.

SETTER, L. R., "Gas Sampling Device for Sanitary Landfill Investigation," *Public Works,* 70(9):45-46 (Sept. 1939).

A gas sampling device was developed for use in New York City's landfills. Having a rigid construction, the device was driven into the refuse with a mallet. The sampler worked quite well and prevented air from entering the gas sample. A cross-sectional drawing and complete description are included.

SOWERS, G. F., "Foundation Problems in Sanitary Landfills," *Journal of the Sanitary Engineering Division,* ASCE, 94(SA1): 103-116 (Feb. 1968).

Landfill gases have caused explosions, serious vegetation kills, and sickness to overexposed persons. Proper foundation design can control gas. Perforated pipes driven into the fill serve as

vents to bleed away the gases. Gastight membranes (two layers thick) spread over vented porous sand serve as good barriers under ground-floor slabs.

The author touches on a variety of construction problems caused by landfills.

STONE, R., E. T. CONRAD, and C. MELVILLE, "Land Conservation by Aerobic Landfill Stabilization," *Public Works*, 99(12): 95-97, 138, 140 (Dec. 1968).

The paper reports results obtained in a demonstration project, which was to demonstrate acceleration of the stabilization in a process in which compacted refuse is aerobically decomposed before final disposal. In the study, a large cell or pit (200 feet long by 50 feet wide by 17 feet deep) was used. It was underlaid with a series of gravel-covered perforated pipes through which air was forced by means of a 1,200 cfm (under 10 inches of water) blower. After the refuse had been aerated for a specific length of time, the "relatively stable" residue was transferred from the aeration pit to a final residue cell where it was compacted again and covered with soil, as is done in conventional sanitary landfill operations. Here anaerobic decomposition took place.

The test material consisted of domestic rubbish and garbage. The aforesaid refuse was about 45 percent (by wet weight) paper or paper in origin, about 45 percent tree and garden trimmings, and about 10 percent garbage. The organic content was about 85 percent, and moisture content ranged from 35 percent in the fall to 80 percent in the spring.

Filling of the first test cell began in June 1967. The filled cell contained 2,940 tons of compacted refuse (overall density—1,253 pounds/cubic yard wet weight). No soil cover was used in the first test; however, one was used in the subsequent tests. The blower cycle during loading (2 months) was 55 minutes on, 35 minutes off, and thereafter (1½ months) 70 minutes on, 20 minutes off. The aeration rate ranged from 225 to 310 cubic feet/cubic yard refuse/day.

Temperatures rose as high as 190 F in the test cell. During the aeration period, the composition of gas samples taken from the cell varied as follows: carbon dioxide from 3 to 19 percent; oxygen from 7 to 17 percent; nitrogen from 67 to 80 percent; and methane from zero to a trace. During the aeration stage in the first run, a fire occurred in the cell contents. Whether or not the fire had an internal or external origin could not be determined. To exclude future external origins, the cell was covered with soil. No fires occurred after the soil cover was used.

At the end of 6 months, the aeration was discontinued and the material was allowed to revert to the anaerobic state. When the gas was measured from the several probes during the next 3-month period, carbon dioxide percentage increased to a range of 57 to 85 percent; oxygen dropped to 0 percent; nitrogen declined to between 1 to 12 percent; and methane rose to a range of 2 to 42 percent. Excluding refuse lost by way of the fire, the volume reduction during the 10-month aeration-nonaeration period was approximately 1,100 cubic yards—that is, slightly less than one-fourth of the original volume. (UC)

U.S. ENVIRONMENTAL PROTECTION AGENCY, *Development of Construction and Use Criteria for Sanitary Landfills,* Final Report, p. III-1 to III-29, unpublished (1971).

This report is on a 3-year gas movement and control study conducted by Los Angeles County, Calif. It contains valuable information on the application of gas control systems.

A gas movement field study was conducted on 10 completed landfills. Information was gathered on soil grain size distribution, classification, specific gravity, dry density, and moisture content at the test sites. Gas probes were installed at each location, and the gases were analyzed for carbon dioxide, oxygen, nitrogen, methane, and hydrogen sulfide concentrations. The report includes complete descriptions of each site; a description of the gas probes and sampling techniques used; and diagrams, tables, and graphs showing gas movement patterns and gas concentration gradients.

The second part of the gas movement study was a laboratory experiment to determine the gas permeability characteristics of a limited range of soils. Methane diffusion-dispersion coefficients were developed for four soil types, each tested at two moisture levels. The results of the experiment indicate the rate of movement of methane by diffusion-dispersion is slower through soils with fine particles than through those with coarser particles for both air-dry and optimum moisture conditions. A complete description of the laboratory apparatus and a table of results are included.

The control of gas movement can be accomplished by using physical barriers or ventilation devices. Barrier devices involve placing some membranes or other substances between the refuse in the landfill and the adjacent soils. Ventilation devices involve the release and venting of gases from or beneath a building. Gas control systems were installed at three of the 10 test sites:

1. Five wells, 30 inches in diameter and 60 feet deep, spaced at 40-foot intervals. Wells were divided into three levels, gravel filled, and each level topped with concrete. Three 6-inch

diameter pipes were installed in each well. These pipes were attached to an 18-inch header which was evacuated by a 25-horsepower blower.

2. A venting system under a 12- by 25-foot greenhouse. Four inches of gravel were placed over 3-inch-diameter perforated pipes. The gravel and pipes were sealed with an airtight covering of asphalt. The pipes were then vented to the atmosphere.
3. A 750-foot trench, 2 feet wide by 6 feet deep with two 24-inch-diameter, 50-foot-deep wells drilled 200 feet apart directly below the trench. Perforated pipe was placed in the wells and trench, and the entire system was filled with gravel, capped with concrete, and vented to the atmosphere.

The report includes schematics of these systems and descriptions of the test run on them.

ZABETAKIS, M. G., "Biological Formation of Flammable Atmospheres," Report RI. 6127, Washington, U.S. Department of the Interior, Bureau of Mines (1962).

The Bureau of Mines Explosives Research Laboratory has investigated six potentially hazardous situations where combustible gases were produced by bacterial action on organic materials. Four of these hazardous situations resulted from the decomposition of landfilled refuse. The recommended controls for relieving hazards in buildings were forced or natural draft venting and gastight foundation construction. A short description of each incident is included.

In each of the six incidents, the hazardous gases were created by the anaerobic decomposition (fermentation) of organic matter. The methane-producing bacteria utilize fatty acids, alcohols, acetone, hydrogen, carbon dioxide, etc., to produce methane.

BIBLIOGRAPHIES AND ABSTRACTS USED AS REFERENCES

American Chemical Society, *Chemical Abstracts,* Columbus, Ohio.

Black, R. J., J. B. Wheeler, and W. G. Henderson, *Refuse Collection and Disposal: an Annotated Bibliography, 1962–1963,* Public Health Service Publication No. 91, Washington, U. S. Government Printing Office, Suppl. F (1966).

Black, R. J., and P. L. Davis, *Refuse Collection and Disposal: an Annotated Bibliography, 1960–1961,* Public Health Service Publication No. 91, Washington, U. S. Government Printing Office, Suppl. E (1963).

Boegly, W. J. Jr., W. L. Griffith, O. M. Sealand, and W. E. Baldry, *Solid Waste Management Practices: an Annotated Bibliography and Permuted-Title and Key-Word Index,* Oak Ridge, Tenn., Oak Ridge National Laboratory (Feb. 1970).

California Department of Public Health, *An Annotated Bibliography for Solid Waste Disposal and Water Quality,* Sacramento (1970).

DeGeare, T. V., R. J. Wigh, and R. A. Young, *Water Quality/Land Disposed Solid Waste: a Bibliography,* Open-File Report (SW-85ts. of), Cincinnati, U. S. Environmental Protection Agency, Solid Waste Management Office (1971).

Engineering Index, Inc., *The Engineering Index,* New York.

Golueke, C. G., *Solid Waste Management: Abstracts and Excerpts from the Literature,* Public Health Service Publication No. 2038, Washington, U. S. Government Printing Office, Vols. I and II. Vol. III in press.

Lefke, L. W., A. G. Keene, R. A. Chapman, and H. Johnson, *Summaries of Solid Wastes Research and Training Grants - 1970,* Environmental Protection Agency Publication, Washington, U.S. Government Printing Office (1971).

Pollution Abstracts, Inc., *Pollution Abstracts,* LaJolla, Calif.

Refuse Collection and Disposal: a Bibliography, 1951–1953, Public Health Service Publication No. 91, Washington, U. S. Government Printing Office, Suppl. A (1953).

Sponagle, C. E., *Summaries: Solid Wastes Demonstration Grant Projects. 1969,* Public Health Service Publication No. 1821, Washington, U. S. Government Printing Office (1969).

Steiner, R. L., and R. Kantz, *Sanitary Landfill–a Bibliography,* 1st ed., Public Health Service Publication No. 1819, Washington, U. S. Government Printing Office (1968).

VanDerwerker, R. J., and L. Weaver, *Refuse Collection and Disposal: a Bibliography, 1941–1950,* Public Health Service Publication No. 91, Washington, U. S. Government Printing Office (1951). Out of print.

Weaver, L., *Refuse Collection and Disposal: an Annotated Bibliography, 1954–1955,* Public Health Service Publication No. 91, Washington, U. S. Government Printing Office, Suppl. B (1963).

Williams, E. R., *Refuse Collection and Disposal: an Annotated Bibliography, 1956–1957,* Public Health Service Publication No. 91, Washington, U. S. Government Printing Office, Suppl. C (1958).

Williams, E. R., and R. J. Black, *Refuse Collection and Disposal: an Annotated Bibliography, 1958–1959,* Public Health Service Publication No. 91, Washington, U. S. Government Printing Office, Suppl. D (1961).

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